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AN INTRODUCTION TO NUCLEAR WEAPONS

By

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FOREWORD

While this document has been published as a Headquarters, U. S. Atomic Energy Commission publication, it has as its genesis two 1954 Los Alamos Scientific Laboratory reports identified as LAMS-1632 and LAMS-1633, titled "Weapons Activities of LASL." These publications are well known and used extensively by those interested in nuclear weapons as basic handbooks on the principles of nuclear weapons development and technology. Dr. Samuel Glasstone has revised and consolidated the above reports incorporating information furnished by the Los Alamos Scientific Laboratory, Lawrence Radiation Laboratory–Livermore, The Sandia Corporation, and the Defense Atomic Support Agency.

This document has been prepared solely for reference purposes on the principles of atomic weapons development and should not be considered as a technical guide for designing nuclear weapons.

Since this issue contains highly sensitive atomic weapons information of significance to our national defense and security, all viewers are enjoined to insure its proper security protection at all times.

A. W. Betts
Major General, USA
Director of Military Application
U. S. Atomic Energy Commission

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ACKNOWLEDGMENT

In preparing this report, I have received invaluable assistance from members of the Lawrence Radiation Laboratory (Livermore), Los Alamos Scientific Laboratory, Defense Atomic Support Agency (Headquarters and Field Command), the Sandia Corporation, and the AEC Division of Military Application. Unfortunately, it is not possible to list the names of all those individuals who contributed either by providing information or by reviewing the draft manuscript or both. However, I wish to acknowledge my great indebtedness to them, for without their help this report could not have been produced. My special thanks are due to Lawrence S. Germain for his effective coordination of the contributions from LRL, Livermore.

S. G.

sion process, but the latter continue to be emitted for a few minutes. For uranium-235 fission, the prompt neutrons constitute 99.35 percent of the total fission neutrons and for plutonium-239 they represent nearly 99.8 percent. Because the time scale in nuclear explosions is very short, delayed neutrons play essentially no part in the fission chain reaction. In reactors for the controlled release of nuclear energy, however, these neutrons are of great significance.

Table 1.1—Neutrons Released per Fission

Nuclide	Neutron Energy ~0 Mev	0.5 Mev	14 Mev
Uranium-235	2.43	2.49	4.1
Plutonium-239	2.80	2.85	4.9
Uranium-233	2.45	2.51	4.2

Fission Energy

1.14 The rough estimate made earlier indicated that about 200 Mev of energy are produced per nucleus undergoing fission. More precise calculations, based on nuclear masses, and experimental measurements have shown that this is a good approximation for both uranium-235 and plutonium-239. The atomic mass in grams, i.e., 235 grams of uranium-235, contains 6.02×10^{23} nuclei, and the complete fission of this amount of uranium-235 would yield $6.02 \times 10^{23} \times 200 = 1.20 \times 10^{25}$ Mev or 1.93×10^{19} erg, since 1 Mev is equal to 1.60×10^{-6} erg. Making use of the fact that 1 calorie is equivalent to 4.18×10^{7} ergs, it can be readily shown that complete fission of all the nuclei in 1 kilogram of fissile material would result in a total energy release of 2.0×10^{13} calories.

1.15 Only part of the energy of fission is immediately available in a nuclear explosion, since most of the radioactive decay energy of the fission products is released over a long period of time. It is usually accepted that about 90 percent of the fission energy contributes to the explosion, so that in a weapon the fission of 1 kilogram of material would produce explosive energy of about 1.8×10^{13} calories. The energy liberated in the explosion of 1 ton of TNT is taken to be 10^{9} calories, and so 1 kilogram of fissile (or fissionable) material is equivalent in explosive power to 18,000 tons, i.e., 18 kilotons (or 18 kt), of TNT.* From these results it is readily found that complete fission of 0.056 kg (or 56 grams) or of 1.45×10^{23} nuclei of fissile material produces the equivalent of 1 kt of TNT of explosive energy. In other words, the energy per fission is 7.03×10^{-24} kt TNT equivalent. In stating the energy yields (or, in brief, the yields) of nuclear weapons, the basic unit, for very low yields, is the ton, with the kiloton (or 1,000 tons), i.e., 1 kt, and the megaton (or 1,000,000 tons), i.e., 1 Mt, of TNT equivalent being used for higher yields.

THE FISSION CHAIN REACTION

Condition for Chain Reaction: Critical Size

1.16 The condition for a self-sustaining fission chain reaction is that, on the average, the neutrons released in one act of fission shall cause (at least) one subsequent fission. Since the average number of neutrons produced in an act of fission is greater than two (see Table 1.1), it would appear, at first sight, that a chain reaction in uranium-235 or plutonium-239 would be inevitable. However, this is not so, because an appreciable proportion of the neutrons pro-

*In some calculations, the equivalent of 1 kg of uranium-235 is assumed to be 17 kt whereas for plutonium-239 it is 19 kt. The value 18 kt per kg is a good average for most fission weapons.

into the fissile core. By reducing the fraction of neutrons which escape completely, a smaller size (or mass) can become critical. Such a scattering material, on account of its function, is sometimes referred to as a neutron reflector.

1.26 In nuclear weapons, the fissile material is surrounded by a tamper or, more specifically, an inertial tamper, the mass of which delays expansion of the exploding material and permits a higher energy yield to be obtained from the system undergoing fission, as will be seen later. This inertial tamper also serves as a neutron reflector or neutronic tamper. In some cases, however, the neutronic aspect is more important than the inertial character of the tamper.

1.27 As is to be expected, increasing the thickness of the tamper decreases the escape of neutrons and thus makes possible a smaller critical mass of the core of fissile material. However, it has been shown by calculations and verified experimentally that when the neutronic tamper thickness reaches a certain value, there is little more to be gained by a further increase of thickness (Fig. 1.2). Thus, when the thickness is about two neutron scattering mean

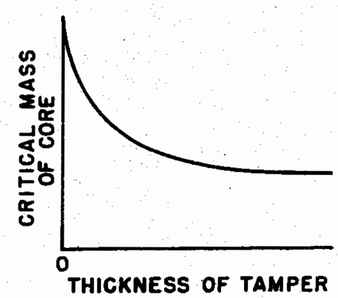

Figure 1.2

free paths, the effectiveness in decreasing the critical mass is within a few percent of that for an infinitely thick tamper.* In natural uranium, which is sometimes used as a tamper, the scattering mean free path of fast (1 Mev) neutrons is about 4 cm, i.e., 1.6 in., in metal of normal density. The value is proportionately less in compressed uranium of higher density. In weapons of low mass, beryllium is a common tamper material; the scattering mean free path is somewhat longer than in uranium because of the lower density.

1.28 Another important factor which affects the critical size is the energy (or speed) of the neutrons causing fission. For several reasons, some of which will be explained later, nuclear weapons are designed so that the fission chain is maintained by fast neutrons, with energies in the range of approximately 0.1 to 2 Mev. In the subsequent treatment it will be assumed, therefore, that fast-neutron fission makes the main contribution to the chain reaction.

Determination of Critical Mass

1.29 Critical masses can now be calculated with a fair degree of accuracy, provided all the conditions are known exactly. It is desirable, however, to check these values by experimental measurements. Because of the danger involved in handling critical assemblies, the general procedure is to extrapolate from observations made on a number of subcritical systems of increasing mass.

1.30 It was seen in §1.20 that the introduction of S neutrons into a fissile material results in the presence of kS neutrons in the first generation, k^2S in the second, and so on. If a

*The scattering mean free path is the average crow-flight distance a neutron travels before undergoing a scattering collision with a nucleus in the given tamper material.

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CHAPTER 2

THE FISSION PROCESS IN WEAPONS

INCREASE OF NEUTRON POPULATION

The Multiplication Rate: Alpha

2.1 No matter how it originates, an explosion is associated with the very rapid liberation of a large amount of energy within a restricted space. If the energy is to be produced by fission, then an essential condition for explosion is a very high neutron density, since the rate of fission, and hence the rate of energy release, is proportional to the number of neutrons per unit volume. It is of interest, therefore, to examine the factors which lead to a high neutron density, since these will form a basis for fission weapon design.

2.2 In accordance with the definition of the effective multiplication factor, k, given in §1.19, it follows that for every n neutrons present at the beginning of a generation there will be nk neutrons at the beginning of the next generation, so that the gain of neutrons is $n(k-1)$ per generation. The rate of gain, dn/dt, may then be obtained upon dividing the actual gain by the average time, τ, between successive fission generations; hence,

$$\frac{dn}{dt} = \frac{n(k-1)}{\tau} \tag{2.1}$$

Equation (2.1) will be strictly correct only if delayed neutrons play no part in maintaining the fission chain. As already stated (§1.13), this condition is applicable, to a good approximation, to nuclear fission weapons.

2.3 The quantity $k-1$, which is the excess number of available neutrons per fission, may be represented by x, i.e.,

$$x \equiv k - 1 \tag{2.2}$$

and then equation (2.1) becomes

$$\frac{dn}{dt} = \frac{x}{\tau} n \tag{2.3}$$

The time rate of increase (or decrease) in neutron population can be expressed in the general form

$$\frac{dn}{dt} = \alpha n \tag{2.4}$$

[redacted]

where α is the specific rate constant for the process which is responsible for the change in the number of neutrons. In nuclear weapons work this constant is called the multiplication rate or merely "alpha." Comparison of equations (2.3) and (2.4) shows that for a fission chain reaction

$$\alpha = \frac{x}{\tau} \tag{2.5}$$

2.4 The foregoing results are applicable regardless of whether x, and hence α, is positive, zero, or negative. For a subcritical system, $k < 1$ (§1.20), i.e., $k - 1$ is negative; in these circumstances x is negative and so also is α. It follows from equation (2.4) that dn/dt is then negative and the number of neutrons in the system will decrease with time. Consequently, in agreement with previous conclusions, the fission chain in a subcritical system will eventually die out because of the steady decrease in the neutron population. When the system is just critical, $k = 1$, and x and α are both zero; the number of neutrons will thus remain constant. Finally, for a supercritical system, $k > 1$, and x and α are positive; there will then be a steady increase in the neutron population. Since dn/dt is proportional to n, by equation (2.4), it is evident that in a supercritical system, the number of neutrons will grow at increasingly faster rates as n increases.

2.5 Another aspect of the significance of α becomes apparent when equation (2.4) is written in the form

$$\frac{dn}{n} = \alpha\, dt$$

If α is assumed to remain constant, this expression can be readily integrated between the time limits of zero, when the number of neutrons present is n_0, and t, when the number is n. The result is

$$n = n_0 e^{\alpha t} \tag{2.6}$$

where, as usual, e is the base of natural logarithms. This expression, like those given above, is applicable regardless of whether α is positive, zero, or negative. If α is known, equation (2.6) can be used to calculate the neutron population at any time t relative to the value at any arbitrary zero time. It can also be seen from equation (2.6) that $1/\alpha$ is the time period during which the number of neutrons changes by a factor e; consequently, $1/\alpha$ is often referred to as the e-folding time, i.e., the time in which there is an e-fold change in the neutron population.

Determination of Alpha

2.6 The value of α is a highly important quantity in weapons design, as will shortly be apparent. Attempts are made to estimate it theoretically from the neutronic and hydrodynamic characteristics of the system, but there are many uncertainties involved and experimental measurements are desirable. In weapons tests, the determination of alpha is one of the most important diagnostic requirements. The methods used under these circumstances are described in Chapter 8. The present treatment will be restricted to procedures which can be used in the design phase without an actual test of the weapon.

2.7 Since a supercritical (or even a critical) mass cannot be handled safely under ordinary conditions, experimental measurements of α are made with a mass that is slightly subcritical. Into this assembly is injected a burst of neutrons and these neutrons initiate a large number of chains. However, since the system is subcritical, α will be negative and so the number of neutrons will decrease after the initial increase. By determining a quantity proportional to the neutron population as a function of time, with neutron counters located outside the assembly, it is possible to determine α by means of equation (2.6). The α obtained from the decrease in neutron population in the early stages is the so-called prompt value, required for weapons studies in which the delayed neutrons play no part.

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2.13 The fission mean free path is equal to $1/N\sigma_f$, where N is the number of fissile nuclei per cm^3 and σ_f is the fission cross section.* Hence, from equation (2.8),

$$\tau \approx \frac{1}{N\sigma_f v} \tag{2.9}$$

so that the generation time is inversely proportional to the produce $\sigma_f v$. The value of σ_f decreases as v increases but the product is 2×10^9 (in 10^{-24} cm^3/sec units) for fast neutrons of 1-Mev energy compared with 10^8 for slow neutrons. Hence, the fission generation time is appreciably shorter for fast than for slow neutrons. Actually, the situation is worse for slow neutrons than would appear from a comparison of the values of $\sigma_f v$ because the effective generation time for these neutrons includes the slowing-down time and this is considerably longer than $\sigma_f v$ alone would indicate.

2.14 From the information already given, it is possible to make a rough, order-of-magnitude estimate of α. As seen from Table 1.1, ν is about 2.5 to 3; the loss, l, of neutrons per fission may be taken as 0.5 to 1, and so, by equation (2.2), x is close to unity for a highly supercritical system. For uncompressed uranium-235 or plutonium-239, the number, N, of nuclei per cm^3 is roughly 0.5×10^{23} and, as seen above, $\sigma_f v$ for fast-neutron fission is $2 \times 10^9 \times 10^{-24}$ cm^3/sec. It follows, therefore, from equation (2.7) and (2.9) that

$$\alpha \approx (0.5 \times 10^{23})(2 \times 10^{-15}) \approx 10^8 \text{ sec}^{-1}$$

Thus, for fast-neutron fission, α is about 10^8 sec^{-1} in a supercritical system and τ, the generation time, is roughly 10^{-8} sec (or 1 shake). It is the common practice to express values of α in reciprocal shakes, i.e., 10^8 sec^{-1} units, so that in the rough calculation made above α is approximately 1 $shake^{-1}$. Experimental measurements, both in the laboratory and at weapons tests, show that α is indeed of this order of magnitude.†

2.15 It is evident that in order to achieve an efficient nuclear explosion, fission should be brought about by fast neutrons, as far as possible. For such neutrons, the factors ν and τ, and to some extent l, favor a high value of α and, hence, a rapid increase in the neutron population. Except in certain special cases, appreciable amounts of elements of low mass number, which slow down neutrons, are consequently kept out of the core of a fission weapon.

2.16 According to equation (2.9), the fission generation time for neutrons of a given energy (or velocity) is inversely proportional to the number, N, of fissile nuclei per cm^3. It follows, therefore, that τ is inversely proportional to η, the core compression ratio; thus

$$\tau \propto \frac{1}{\eta} \tag{2.10}$$

Consequently, the generation time can be decreased, and the value of α increased, by compression of the core material.

2.17 In addition to the effect on τ, compression also causes a marked decrease in l, for the reason given in §1.40. This also contributes to an increase in α, as follows from equation (2.7). It is seen, therefore, that compression of the core will cause an increase in α because of the decrease in both τ and l.

Explosion Time

2.18 According to the arguments in §2.14, x is approximately equal to unity and so, by equation (2.5), $1/\alpha$ is roughly equal to τ, the generation time. It is thus possible to write equation (2.6) in the approximate form

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*For the present purpose it is sufficient to regard the cross section as the effective area in sq cm of a nucleus for a particular reaction (or reactions). Cross sections vary with the neutron energy and the fission cross sections for uranium-235 and plutonium-239 have been measured over a large energy range.

†Some workers prefer to express α in reciprocal microseconds.

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efficiencies were estimated by the method of Bethe and Feynman. The basic formula is admittedly approximate, since it involves several simplifying assumptions. However, its derivation is useful in the respect that it provides a model of the explosion of a fission weapon and indicates, qualitatively at least, some of the factors which affect the efficiency of the explosion. The treatment given below is applicable to pure fission systems and not after boosting occurs.

2.29 As a result of the energy liberated in fission, very large pressures (~10^9 atm) are developed in the core, and the core-tamper interface consequently receives a large outward acceleration. This causes highly compressed tamper material to pile up just ahead of the expanding interface, in an effect referred to as the "snowplow" phenomenon, because of the similarity to the piling up of snow in front of a snowplow. The inertia of the compressed tamper delays expansion of the core, so that a considerable pressure gradient builds up from the center of the core to its outer surface.

2.30 Furthermore, because of the delayed expansion, it may be supposed that the volume of the compressed (supercritical) core remains essentially constant during the first [redacted] DOE b(3) so generations following initiation of the fission chain, i.e., up to explosion time. After this interval, almost the whole of the energy is released within an extremely short period, during which time the supercritical core expands rapidly until it becomes subcritical. Although there is an appreciable release of energy even while the system is subcritical, as mentioned in §2.27, it will be postulated that energy production ceases when the dimensions are just critical. It will be assumed, further, that no energy escapes during the short period of expansion from maximum supercriticality to the point where the system becomes subcritical.

2.31 Let R be the radius of a spherical core at the point of maximum supercriticality; then, in accordance with the postulate made above, this will remain unchanged until explosion time. Subsequently, the energy density of the system becomes so large that mechanical effects begin and the core starts to expand. Suppose that when the core has expanded by a fraction δ, so that the radius is $R(1 + \delta)$, the system is just critical (Fig. 2.1); beyond this point it will be subcritical. The self-sustaining fission chain will then end and, in accordance with the approximation postulated above, there will be no further release of energy.

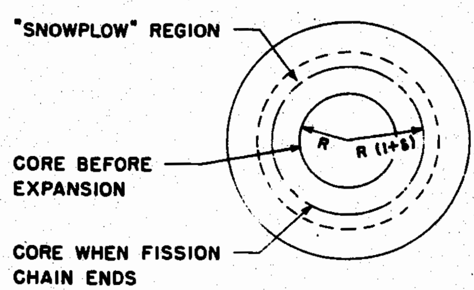

Figure 2.1

2.32 Consider a thin shell of material in the core, of volume dV and thickness dR; the cross sectional area of the shell is then dV/dR. If dP is the pressure difference on the two sides of this shell, caused by the liberated fission energy, the net outward force, dF, to which the shell is subjected, i.e., pressure × area, is then

$$dF = dP\frac{dV}{dR} = \frac{dP}{dR}dV \qquad (2.14)$$

where dP/dR is the pressure gradient in the given shell. As a reasonable approximation, it may be supposed that the pressure gradient is essentially constant across the core radius, so that

$$\frac{dP}{dR} \approx \frac{P}{R} \tag{2.15}$$

where P is the total difference in pressure from the center of the core to the outer surface before expansion occurs. Hence, from equations (2.14) and (2.15),

$$dF \approx \frac{P}{R} dV \tag{2.16}$$

2.33 The time required for the core to expand from radius R to R(1 + δ), i.e., a distance of Rδ, is about 7 generations, as seen in §2.21. However, as a rough approximation, this may be taken as $1/\alpha$, where α is the multiplication rate just prior to explosion time. The mean outward acceleration of the core material, and of the shell dV, may consequently be expressed as $R\delta\alpha^2$. The mass of the shell is ρdV, where ρ is the core density; hence, by Newton's second law of motion, i.e., force = mass × acceleration, the force dF acting on the shell is given by

$$dF \approx \rho dV \times R\delta\alpha^2$$

Upon comparing this result with equation (2.16), it is seen that

$$P \approx \rho R^2\alpha^2\delta \tag{2.17}$$

2.34 At the existing temperature the core will be gaseous and if, as postulated, the loss of energy from the system during the initial expansion is negligible, it may be considered as a gas undergoing an adiabatic process. The total energy of such a gas, which may be taken to be equal to the energy of the core, is then

$$E = \frac{PV}{\gamma - 1} \tag{2.18}$$

where γ is the ratio of the specific heats of the gas. Using equation (2.17) for P and writing M/ρ for the volume of the core, M being the mass, equation (2.18) becomes

$$E \approx \frac{MR^2\alpha^2\delta}{\gamma - 1} \tag{2.19}$$

2.35 If ϵ is the energy released in the complete fission of unit mass of core material, then the total energy available in the core is $M\epsilon$, and the efficiency, according to equation (2.13), is $E/M\epsilon$, where E is given by equation (2.19); consequently,

$$\phi = \frac{E}{M\epsilon} \approx \frac{R^2\alpha^2\delta}{(\gamma - 1)\epsilon} \tag{2.20}$$

It should be pointed out that in the foregoing derivation no allowance has been made for depletion of the core material as fission proceeds. For low efficiencies, to which most of the other approximations made are applicable, the depletion is not significant and can be neglected. Moreover, no allowance has been made for the inertial effect of the tamper on the efficiency. For the present purpose, which is to obtain a qualitative guide to some of the factors determining the efficiency, this can also be ignored. Hence, replacing the quantity $1/(\gamma - 1)\epsilon$ by a constant, K, equation (2.20) can be written as

$$\phi \approx KR^2\alpha^2\delta \tag{2.21}$$

[redacted] DOE b(3)

2.40 The avoidance of preinitiation was therefore an important aspect of the design of simple fission weapons. The neutron sources which served as initiators were constructed so as to produce a burst of neutrons as close as possible to the optimum time, and the neutron background from the fissile material was maintained within reasonable bounds. In all-plutonium cores, relatively clean (20 ngs) material was used and dirtier plutonium was employed only in composite cores which contained oralloy in addition, with the latter in excess. Such a utilization of fissile material was desirable in any event, for reasons given in §3.21 et seq.

2.41 The behavior of the solid core in an unboosted implosion weapon is somewhat as follows. [redacted] DOE b(3) At first critical, α is zero and it increases steadily as compression of the core proceeds. Just before maximum compression, when α is approaching its maximum value, neutrons are injected into the highly supercritical system. The divergent fission chain is initiated and energy is released. [redacted] DOE b(3) DOE b(3) This condition is referred to as "second critical" (Fig. 2.2). Both the neutron density and the rate of the fission reaction are now at a maximum. Beyond second critical, α becomes negative and the neutron density decreases, in accordance with equation (2.6). Although a self-sustaining chain is no longer possible, considerable amounts of energy are produced by the convergent fission chains in the subcritical system.

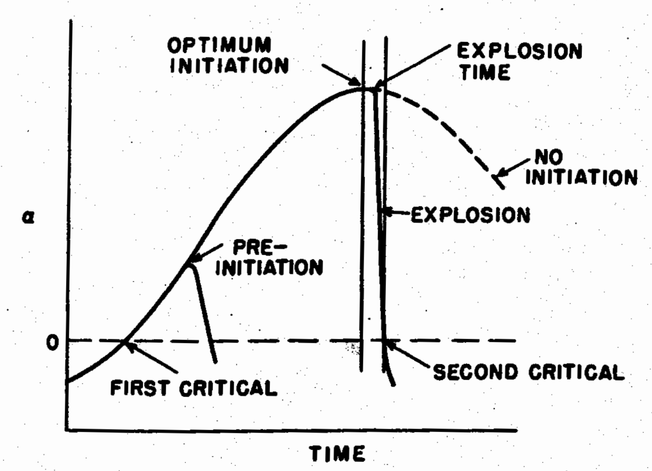

Figure 2.2

Boosted Implosion Systems

2.42 In modern boosted, implosion-type fission weapons, the situation is quite different from that described above. The cores are hollow, subcritical shells which contain the deuterium-tritium boosting gas. [redacted] DOE b(3)